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## Optical and Magnetic Properties of Dust Grains

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**Abstract.** The optical and magnetic properties of dust grains are reviewed, as they relate to the problem of interstellar grain alignment. Grain geometry plays an important role in determining the optical properties, and scattering and absorption of starlight will produce radiative torques which may drive grains to suprathermal rates of rotation in interstellar clouds; these radiative torques appear likely to play an active role in the alignment process. The likely magnetic properties of grains are discussed, with particular attention to the imaginary part of the magnetic susceptibility.

### 1. Introduction

What physical processes are responsible for the observed alignment of interstellar dust grains? The answer to this question has proved remarkably elusive. The first major theoretical assault on this problem was the classic paper by Davis & Greenstein (1951), who examined many of the physical processes involved, and proposed that grain alignment was the result of magnetic dissipation within spinning grains. While other alignment mechanisms are possible – in particular, alignment by gas-grain streaming (Gold 1952; Roberge & Hanany 1990; Lazarian 1994) – the process of grain alignment by magnetic dissipation has continued to appear attractive, and has received continuing theoretical attention.

In this paper I review some optical and magnetic properties of grains, as they relate to the problem of grain alignment. There is little we can say for certain about the composition, sizes, and geometry of interstellar grains; our current state of understanding is summarized in §§2.1.,2.2. At first sight it is not apparent how the optical properties can affect grain alignment; in §2.3. a mechanism is discussed whereby radiation field anisotropy can result in substantial torques on interstellar grains. These radiative torques may produce both suprathermal rotation and grain alignment.

The efficacy of grain alignment by magnetic dissipation obviously depends on the magnetic properties of dust grains, reviewed in §3. Since we do not know what grains are composed of, their magnetic properties are necessarily uncertain; various possibilities are discussed. “Ordinary” paramagnetism appears to be marginally capable of producing grain alignment in suprathermally rotating grains. It seems quite possible, however, that at least some interstellar grains may contain ferromagnetic inclusions, which can enhance the rate of magnetic

dissipation either by “superparamagnetism” or by subjecting adjacent paramagnetic material to a static magnetic field.

## 2. Optical Properties of Grains

### 2.1. Grain Composition

Spectroscopy of interstellar dust began with the discovery by Merrill (1934) that 4 diffuse bands were of interstellar origin. It is humbling to realize that over 60 years later – and 30 years after dust grain spectroscopy was extended to the ultraviolet and infrared – we still do not have *any* certain identification of interstellar grain composition.

Observations and theories of interstellar dust have been reviewed recently by various authors (Mathis 1993; Draine 1994, 1995). Elsewhere in this volume, Mathis (1996) gives an excellent summary of observational constraints on dust models, stressing how little we can say with confidence concerning grain composition. I would summarize our knowledge of the composition of grains in diffuse clouds as follows:

- The  $9.7\mu\text{m}$  and  $18\mu\text{m}$  features almost certainly require that a substantial fraction ( $\gtrsim 50\%$ ) is in some form(s) of silicate material. Probably this material contains most of the Mg, Si, and Fe in the interstellar medium, and perhaps 10–20% of the O.
- The strong  $2175\text{\AA}$  “bump” is very likely to be due to some form of carbon in  $a \lesssim 200\text{\AA}$  grains (Draine 1989). The carbon material is likely to be graphitic in nature (i.e., primarily  $sp^2$  bonding). Approximately 14% of the interstellar carbon must be in this form
- The  $3.4\mu\text{m}$  C-H stretch indicates that some form of aliphatic hydrocarbon is present.
- Meteoritic studies tell us that diamond, SiC, TiC, and  $\text{Al}_2\text{O}_3$  are present in interstellar space at some (unknown) low level.

Beyond this, we can say little about the composition of grains in diffuse clouds. Spectroscopy of dust in dark clouds reveals a host of additional condensed species such as  $\text{H}_2\text{O}$ , CO, and  $\text{CH}_3\text{OH}$  (cf. van Dishoeck et al. 1993, Table VIII), but grains in diffuse clouds appear to be devoid of these “ice” features.

The overall wavelength-dependence of interstellar extinction and polarization allows some general conclusions regarding the size distribution of interstellar dust:

- The grain size distribution must include grains as large as  $\sim 0.2\mu\text{m}$  and as small as  $0.01\mu\text{m}$ .
- The size distribution may be approximated by the “MRN distribution”,  $dn/da \propto a^{-3.5}$  (Mathis, Rumpl, & Nordsieck 1977; Kim, Martin, & Hendry 1994), with most of the volume contributed by the large particles, and most of the surface area contributed by small particles

- The observed wavelength-dependent polarization indicates that the larger particles ( $a \gtrsim 0.1\mu\text{m}$ ) are both nonspherical and fairly well aligned, but the smaller particles ( $a \lesssim .05\mu\text{m}$ ) are either spherical or poorly aligned (Kim & Martin 1995).

## 2.2. Grain Geometry

The optical properties of grains depend on geometry as well as composition; unfortunately, the likely grain geometry is controversial. The MRN model (Mathis, Rumpl, & Nordsieck 1977; Draine & Lee 1984) approximates the grains as solid spheres. The observed interstellar polarization of course indicates that the grains cannot all be spherical, but the optical properties of spheroids (with moderate axial ratio) are not greatly different from those of spheres, and spheroids can reproduce the observed polarization (Kim & Martin 1995). Mathis & Whiffen (1989), however, favor the idea that at least the  $a \gtrsim 0.05\mu\text{m}$  grains are fluffy aggregates of smaller particles. In any case, we can be certain that Nature has *not* populated the ISM with spheres or spheroids – the complex evolution of interstellar grains (Draine 1990; Dorschner & Henning 1996) seems guaranteed to produce irregular structures, whether “fluffy” or not.

## 2.3. Radiative Torques on Irregular Grains

Purcell (1979) pointed out 3 separate processes which may result in suprathermal grain rotation: inelastic scattering of impinging atoms when the gas and grain temperature differ, photoelectric emission, and  $\text{H}_2$  formation on grain surfaces. Here we call attention to a new mechanism which may produce suprathermal rotation of interstellar grains: radiative torques on grains illuminated by anisotropic starlight.

The possibility of spinning up grains by illuminating them with anisotropic radiation was considered by Harwit (1970a,b), who noted that if a grain illuminated by a point source absorbed different numbers of left- and right-circularly-polarized photons, it would acquire a net angular momentum parallel or antiparallel to the photon’s direction of propagation. Harwit considered symmetric grains, and estimated the rms value of the grain angular momentum resulting from the stochastic nature of photon absorption. Purcell & Spitzer (1971) showed, however, that this angular momentum is small compared to that resulting from the radiation-pressure-driven gas-grain streaming

Dolginov (1972) and Dolginov & Mytrophanov (1976) pointed out that a typical interstellar grain may possess a certain amount of “helicity” if it is made of optically-active material, or simply has an irregular shape, so that the scattering and absorption cross sections will differ for the two circular polarization states. As a result, if the grain is subject to an unpolarized but anisotropic radiation field, there will be a systematic torque.

While in principle such “helicity” should exist, it has not been apparent how effective it will be in producing torques on interstellar grains, because of the difficulty in calculating electromagnetic cross sections for irregular grains. This has recently been investigated by Draine & Weingartner (1996), using the discrete dipole approximation (Draine & Flatau 1994) to calculate the torques on grains illuminated by a beam of unpolarized radiation. They considered a moderately irregular grain, which does not appear – to the eye – to be obviously

“helical”. Their results indicate that, at least for this grain, a typical radiation field in a diffuse cloud will torque the grain up to suprathermal rotation velocities.

As noted by Purcell (1979), if suprathermal grain rotation can be maintained by “thrusters” which are fixed relative to the grain surface (e.g., preferred sites for  $\text{H}_2$  formation), then Davis-Greenstein alignment will occur inexorably. If the “thrusters” on the grain surface are stable for periods long compared to  $\tau_{DG}$ , then high degrees of grain alignment will result. The problem with this explanation for observed grain alignment is that it seems questionable whether the grain surface properties responsible for the suprathermal rotation remain stable for the millions of years necessary for grain alignment by normal paramagnetic dissipation. The radiative torque driving suprathermal rotation is, however, determined by the overall grain “helicity”, and one expects this helicity to have a lifetime comparable to the  $\sim 3 \times 10^8$  yr lifetime of a refractory grain (Draine & Salpeter 1979; Jones et al. 1994) – much longer than the timescale for altering the monolayer or so of atoms determining the surface properties. There is a preferred direction in the problem: that characterizing the anisotropy in the radiation field; this may be the direction to the galactic center (*very* stable!) or the nearest bright stellar association (probably stable for  $\sim 10^7$  yr). As a result, suprathermal rotation driven by radiative torques may result in appreciable degrees of grain alignment even if grains have only ordinary paramagnetic properties.

It is also important to note that the torque on the grain depends on the grain orientation relative to the radiation anisotropy, so that the radiative torques can actually play a direct role in the grain alignment process.

Finally, the existence of a new mechanism for driving suprathermal rotation of course does not mean that the previously-proposed mechanisms ( $\text{H}_2$  recombination, variations in accommodation coefficient, photoelectric emission) cease to operate: the dynamics of the grain will be determined by all of these acting in concert.

### 3. Magnetic Properties of Dust Grains

#### 3.1. Alignment by Magnetic Dissipation

The magnetic properties of grains are of interest primarily because of the possibility that magnetic dissipation may be responsible for the observed alignment of interstellar dust, as originally proposed by Davis & Greenstein (1951). The Davis-Greenstein timescale for alignment by magnetic dissipation for a grain of radius of gyration  $a = 10^{-5} a_{-5}$  cm is

$$\tau_{DG} = \frac{2\rho a^2}{5K(\omega)H^2} = 1.2 \times 10^6 a_{-5}^2 \left( \frac{\rho}{3 \text{ g cm}^{-3}} \right) \left( \frac{10^{-13} \text{ s}}{K(\omega)} \right) \left( \frac{5 \mu\text{G}}{H} \right)^2 \text{ yr} \quad , \quad (1)$$

where  $\omega$  is the angular velocity of the grain,  $H$  is the interstellar magnetic field,  $\rho$  is the grain density, and

$$K(\omega) \equiv \frac{\text{Im}[\chi(\omega)]}{\omega} \quad , \quad (2)$$

where  $\chi(\omega)$  is the complex susceptibility of the grain material. The interstellar magnetic field is now thought to have an rms value  $H \approx 5\mu\text{G}$  (Heiles 1995, 1996). If  $K(\omega) \gtrsim 10^{-13}\text{ s}$ ,  $\tau_{DG}$  is short enough for magnetic dissipation to play a significant role in grain alignment.

Interstellar grains rotate rapidly; if the grain spin axis is not aligned with the external field  $H$ , then the component of  $H$  transverse to the spin axis will appear (in the “grain frame”) to be rotating with a frequency equal to the grain rotational velocity  $\omega$ . The angular velocity for a sphere is

$$\omega = \left( \frac{45kT_{rot}}{8\pi\rho a^5} \right)^{1/2} \approx 3 \times 10^5 a_{-5}^{-2.5} \left( \frac{3\text{ g cm}^{-3}}{\rho} \right)^{1/2} \left( \frac{T_{rot}}{100\text{ K}} \right)^{1/2} \text{ s}^{-1} \quad , \quad (3)$$

where  $3kT_{rot}/2$  is the rotational kinetic energy. “Thermal” rotation would have  $T_{rot} = T_{gas} \approx 10^2\text{ K}$ , but various effects are expected to result in much larger “suprathermal” rotation rates (Purcell 1979). We therefore need to understand the response of materials to magnetic fields at frequencies  $10^5 \lesssim \omega \lesssim 10^9\text{ s}^{-1}$ .

### 3.2. Paramagnetism

Most materials contain unpaired electrons in partially-filled shells [see Morrish (1980) for a general introduction to magnetism]. Let  $\mu = p\mu_B$  be the magnetic moment of the electrons in the outer, partially-filled shell, where  $\mu_B \equiv e\hbar/2m_e c$  is the Bohr magneton.  $\text{Fe}^{2+}({}^5D_4)$  and  $\text{Fe}^{3+}({}^6S_{5/2})$  ions have  $p \approx 5.4$  and  $5.9$ , respectively (Morrish 1980). In numerical examples below we will take  $p \approx 5.5$ .

Let the number density of “paramagnetic” atoms with partially-filled shells be  $n_p = f_p n_{tot}$ , where  $n_{tot} \approx 10^{23}\text{ cm}^{-3}$  is the total atomic density, and  $f_p$  is the fraction of the atoms which are paramagnetic. Since observations of interstellar depletions indicate that  $\sim 10\%$  of the atoms in grains are Fe, it will be reasonable to consider values of  $f_p$  as large as  $\sim 0.1$ .

If the exchange interaction and interactions among the spins do not induce long-range order, then the spin system will be paramagnetic. For a static field the paramagnetic susceptibility is given by Curie’s Law (Morrish 1980):

$$\chi(0) = \frac{n_p \mu^2}{3kT} = 4.2 \times 10^{-2} f_p \left( \frac{n_{tot}}{10^{23}\text{ cm}^{-3}} \right) \left( \frac{p}{5.5} \right)^2 \left( \frac{15\text{ K}}{T} \right) \quad . \quad (4)$$

$K(\omega)$  must satisfy the Kramers-Kronig relation (Landau & Lifshitz 1960)

$$\chi(0) = \frac{2}{\pi} \int_0^\infty K(\omega) d\omega \quad . \quad (5)$$

Since  $\chi(0)$  is known, this strongly constrains  $K(\omega)$  – its integral over frequency is fixed.

The precise behavior of  $K(\omega)$  is uncertain. For  $\omega \rightarrow 0$  we expect  $\text{Im}\chi \propto \omega$ , or  $K \propto \omega^0$ . From eq.(5) it is clear that for  $\omega \rightarrow \infty$ ,  $K(\omega)$  must decrease *more* rapidly than  $\omega^{-1}$ . Two commonly-assumed forms are

$$K(\omega) = \frac{\chi(0)\tau}{1 + (\omega\tau)^2} \quad , \quad (6)$$

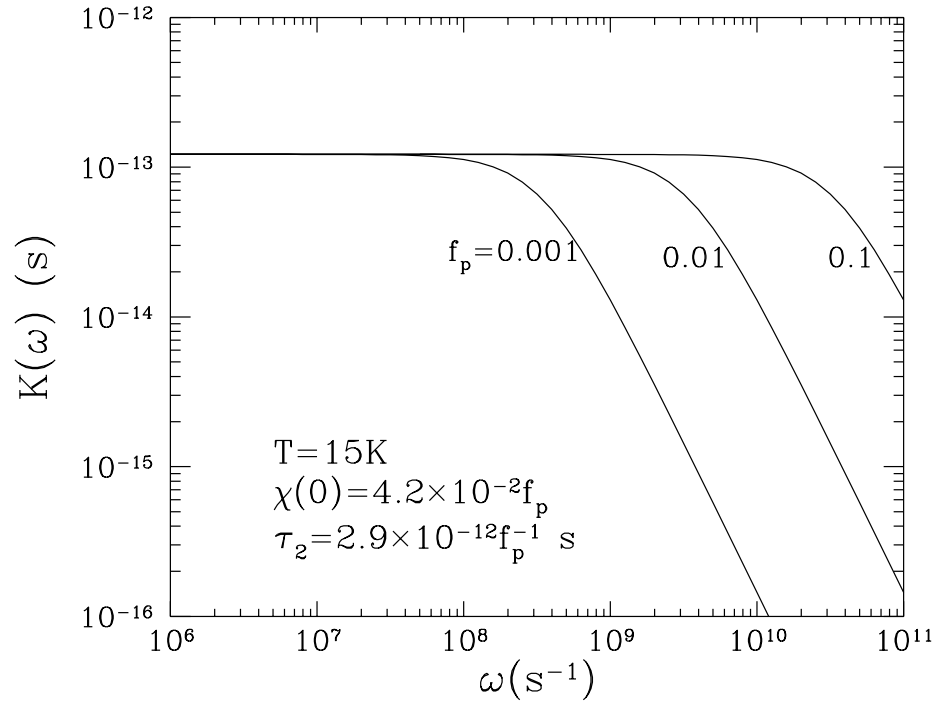


Figure 1.  $K(\omega) = \text{Im}[\chi(\omega)]/\omega$  for paramagnetic grains (see text);  $f_p$  is the fraction of the atoms which are Fe.

and

$$K(\omega) = (\pi/2)^{1/2} \chi(0) \tau \exp \left[ -(\omega\tau)^2/2 \right] \quad . \quad (7)$$

We see that for a given  $\tau$  and  $\chi(0)$ , these differ for  $\omega \ll \tau^{-1}$  by only a factor  $(\pi/2)^{1/2}$ . We will assume  $K$  to be given by eq.(6) in discussion below.

There are *two* distinct relaxation processes – spin-spin relaxation and spin-lattice relaxation – but Jones & Spitzer (1967) showed that only spin-spin relaxation is relevant for paramagnetic grains spinning in a weak magnetic field. Each magnetic moment is subject to strong “internal” magnetic fields produced by the other magnetic moments, with rms value  $H_i \approx 3.8n_p\mu$  (van Vleck 1937). The spin-spin coupling time  $\tau_2$  should be approximately equal to the inverse of the precession frequency in a field  $H_i$ ,

$$\tau_2 \approx \frac{\hbar}{g\mu_B H_i} = \frac{\hbar}{3.8n_p p g \mu_B^2} = 2.9 \times 10^{-12} f_p^{-1} \text{ s} \quad , \quad (8)$$

where we have taken  $p = 5.5$  and  $g = 2$ . This is a factor  $\sim 4$  larger than the theoretical estimate of Broer (1943), but appears to be in fairly good agreement with the experimental results given by Morrish (1980, Table 3-6.1). With this value of  $\tau_2$  we obtain

$$K(\omega) = \frac{\hbar p}{11.4 g k T} \frac{1}{1 + (\omega\tau_2)^2} \approx 1.2 \times 10^{-13} \left( \frac{15 \text{ K}}{T} \right) \frac{1}{1 + (\omega\tau_2)^2} \text{ s} \quad . \quad (9)$$

This is  $\sim 30\%$  smaller than the estimates of Jone & Spitzer (1967) and Spitzer (1978), reflecting uncertainties in estimation of  $\tau_2$  and the form of the function  $K(\omega)$ . In Figure 1 we plot  $K(\omega)$  as a function of grain rotation frequency for different values of  $f_p$ .

### 3.3. Antiferromagnetic Minerals?

We note that some Fe-rich minerals are antiferromagnetic: below the Neél temperature  $T_N$ , the magnetic moments are ordered but in such a way that the net magnetization is zero. At  $T > T_N$ , the material behaves approximately like an ordinary paramagnetic substance, but for  $T \ll T_N$  the susceptibility is below the value expected from eq. (4). Examples of potential interest include troilite (FeS,  $T_N = 600 \text{ K}$ ; Carmichael 1989), wustite (FeO,  $T_N = 188 \text{ K}$ ; Carmichael 1989), fayalite (Fe<sub>2</sub>SiO<sub>4</sub>,  $T_N = 65 \text{ K}$ ; Strangway 1981), and pyroxene (FeSiO<sub>3</sub>,  $T_N = 40 \text{ K}$ ; Carmichael 1989). At the temperatures  $T < T_N$  of interstellar grains, macroscopic crystals of these materials would have very small susceptibilities [e.g., Fe<sub>2</sub>SiO<sub>4</sub> has  $\chi(0) = 1 \times 10^{-3}$  at  $T = 15 \text{ K}$  (Santoro, Newnham & Nomura 1966), a factor  $\sim 10$  below what would have been estimated from eq.(4)]. We note, however, that interstellar grains are (a) unlikely to be crystalline (or will have extremely small microcrystallites) and (b) are unlikely to be strictly stoichiometric. As a result, ideal antiferromagnetism is unlikely to occur: there should always be a reasonable number of uncompensated magnetic ions. Indeed, although NiO is antiferromagnetic for  $T < 523 \text{ K}$ , weak ferromagnetism has been observed in small ( $d \lesssim 400 \text{ \AA}$ ) particles (Richardson & Milligan 1956; Schuele & Deetscreek 1962). We therefore expect Fe-containing interstellar grains to be either paramagnetic, superparamagnetic, ferrimagnetic, or ferromagnetic.

### 3.4. Superparamagnetism

As originally proposed by Jones & Spitzer (1967), interstellar grains may contain “superparamagnetic” inclusions, in which a cluster of atoms spontaneously magnetizes into a single domain, behaving like a single large magnetic moment. This can occur for clusters of materials which are ferromagnetic (e.g., Fe) or ferrimagnetic, such as magnetite ( $\text{Fe}_3\text{O}_4$ ) or maghemite ( $\gamma\text{Fe}_2\text{O}_3$ ).

We consider Fe for purposes of discussion. Single-domain behavior occurs for clusters as small as 20 atoms (Billas, Châtelain & de Heer 1994) or as large as  $5 \times 10^5$  (Kneller & Laborsky 1963). Let us now suppose that a fraction  $f_p$  of the atoms are magnetic, and aggregated in clusters of  $N_{cl}$  atoms per cluster. Let  $p\mu_B$  be the effective magnetic moment per Fe atom; bulk Fe has  $p = 2.22$  (Morrish 1980) while  $p$  increases to  $p \approx 3$  for  $N_{cl} \lesssim 150$  (Billas et al. 1994). The zero-frequency susceptibility is now increased by a factor  $N_{cl}$ :

$$\chi(0) = 1.2 \times 10^{-2} N_{cl} f_p \left( \frac{n_{tot}}{10^{23} \text{ cm}^{-3}} \right) \left( \frac{p}{3} \right)^2 \left( \frac{15 \text{ K}}{T} \right) . \quad (10)$$

When the applied field changes direction, the individual atom moments in a cluster must collectively rotate. If the cluster is not spherical, or the material is anisotropic, this change in direction may require an increase in the magnetic energy of the cluster. As a result, the cluster may have to overcome an energy barrier before the magnetization is able to reorient; the energy barrier is proportional to the cluster volume. The relaxation process is therefore thermally activated, with a rate

$$\tau_{sp}^{-1} \approx \nu_0 \exp[-N_{cl}\theta/T] , \quad (11)$$

where  $\nu_0 \approx 10^9 \text{ s}^{-1}$  and  $\theta \approx .011 \text{ K}$  for metallic Fe spheres (Bean & Livingston 1959; Jacobs & Bean 1963; Morrish 1980) [note that this value for  $\theta$  is a factor  $\sim 6.6$  smaller than the value estimated by Jones & Spitzer (1967) from Brown (1959)]. With this relaxation time, we estimate

$$K(\omega) = \frac{n_p N_{cl} p^2 \mu_B^2}{3\nu_0 kT} \frac{\exp(N_{cl}\theta/T)}{1 + (\omega\tau_{sp})^2} = \frac{1.2 \times 10^{-11} f_p N_{cl} e^{.011 N_{cl}/T}}{1 + (\omega\tau_{sp})^2} ; \quad (12)$$

$K(\omega)$  is plotted in Figure 2 for  $f_p = 0.01$  and selected values of  $N_{cl}$ .

We see from Figure 2 that if 1% of the atoms in the grain are Fe atoms in clusters and the grain rotational velocity is approximately “thermal” ( $10^5 \lesssim \omega \lesssim 10^6 \text{ s}^{-1}$ ), then  $K \gtrsim 10^{-12} \text{ s}$  provided the clusters are not too large,  $N_{cl} < 3.5 \times 10^4$ ; this corresponds to cluster diameters  $d = 2.83 N_{cl}^{1/3} \text{ \AA} < 93 \text{ \AA}$ . Very large values of  $K(\omega)$  are possible for  $10^3 \lesssim N_{cl} \lesssim 2 \times 10^4$ : a *single* cluster of  $N_{cl} = 5000$  Fe atoms would give a grain an effective  $K \approx 3 \times 10^{-11} \text{ a}_{-5}^{-3} \text{ s}$ .

On the other hand, if the grain is very small, or if the grain rotational velocity is highly suprathreshold, only small clusters will be able to provide appreciable superparamagnetic damping: e.g., if  $\omega = 10^9 \text{ s}^{-1}$ , then only clusters with  $N_{cl} < 1 \times 10^4$  ( $d < 60 \text{ \AA}$ ) will be effective.

How likely is it that interstellar grains will contain clusters of  $30 - 3 \times 10^4$  Fe atoms, with diameters  $9 - 90 \text{ \AA}$ ? It is difficult to say, but Martin (1995) has observed that the interplanetary dust particles referred to as GEMS (Glasses with



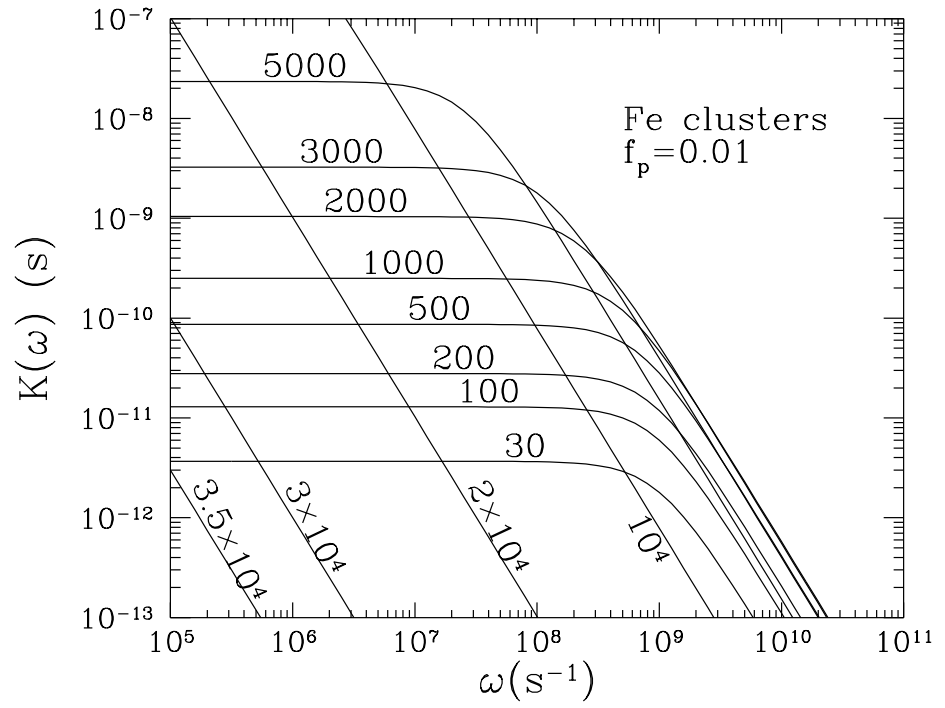


Figure 2.  $K(\omega)$  for material containing superparamagnetic clusters; curves are labelled by  $N_{cl}$ , the number of Fe atoms per cluster. It is assumed that 1% of the atoms are in such clusters.

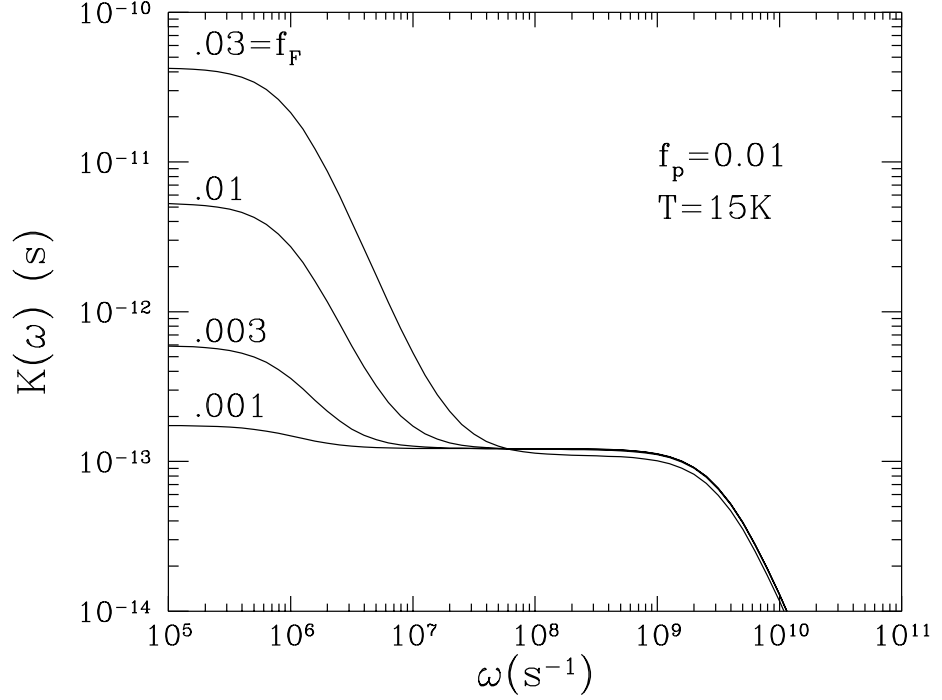


Figure 3.  $K(\omega)$  for paramagnetic material with a fraction  $f_F$  of the atoms in ferromagnetic inclusions, for  $\tau_1 = 10^{-6}$  s.

Embedded Metals and Sulfides; Bradley 1994), which may well be of interstellar origin, do contain small metal-rich inclusions, possibly superparamagnetic; this idea has been further stressed by Goodman & Whittet (1996). Mathis (1986) proposed that the observed variation of degree of grain alignment with grain size could be understood as reflecting the probability of one or more superparamagnetic inclusions being present in a grain; in Mathis's model, a grain of radius 800Å has a ~50% probability of containing one or more superparamagnetic inclusions.

The idea of grain alignment being due to superparamagnetic inclusion is quite attractive: it is physically plausible, and it provides a “natural” explanation for the observed wavelength-dependence of polarization. If GEMS are found to be of interstellar origin, laboratory studies of the magnetic properties of their inclusions will permit this hypothesis to be tested.

### 3.5. Ferromagnetic + Paramagnetic Grains

Duley (1978) pointed out that if interstellar grains contain ferromagnetic or ferromagnetic inclusions, then these inclusions will subject nearby paramagnetic material to a constant magnetic field; the presence of this field can substantially increase the dissipation provided by the paramagnetic substance, thereby enhancing the grain alignment process. When a static field  $H_0$  is applied parallel to the oscillating field  $He^{i\omega t}$ , the paramagnetic response involves the spin-lattice

relaxation time  $\tau_1$  as well as the spin-spin relaxation time  $\tau_2$ :

$$K(\omega) = F \frac{\tau_1}{1 + (\omega\tau_1)^2} + (1 - F) \frac{\tau_2}{1 + (\omega\tau_2)^2} \quad , \quad (13)$$

where  $F$  is given by the Casimir-Dupré relation (Morrish 1980),

$$F = \frac{H_0^2}{H_0^2 + H_c^2} \quad , \quad H_c = \left[ \frac{C_M T}{\chi(0)} \right]^{1/2} \quad ; \quad (14)$$

$C_M$  is the heat capacity per volume at constant magnetization. Various paramagnetic salts have  $H_c \approx 10^3$  Oe, approximately independent of temperature (Gorter 1947). The value of the spin-lattice relaxation time  $\tau_1$ , which may depend on both temperature and magnetic field, is uncertain; we will take  $\tau_1 \approx 10^{-6}$  s for purposes of discussion, but values much longer or much shorter are possible (Morrish 1980).

If a fraction  $f_F$  of the atoms are in single-domain ferromagnetic clusters, then the rms value of the resulting magnetic field component along a given direction outside the clusters will be

$$H_0 \approx 3.8 f_F n_{tot} p \mu_B / \sqrt{3} \approx 100 (f_F / .01) \text{ Oe} \quad . \quad (15)$$

In Figure 3 we show the magnetic susceptibility computed for the paramagnetic grain material (with  $f_p = 0.01$ ); curves are labelled by the fraction  $f_F$  of the atoms assumed to be in ferromagnetic clusters. We see that for  $f_F \gtrsim 0.01$  and  $\omega \lesssim 10^6 \text{ s}^{-1}$ ,  $K(\omega)$  can be substantially larger than the estimate (9) based on spin-spin dissipation only. (We note, however, that this enhancement is quite sensitive to the very uncertain value of  $\tau_1$ .) Because  $\int K(\omega) d\omega \propto \chi(0)$  is fixed, the enhancement of  $K(\omega)$  at low frequencies is accompanied by a suppression of  $K(\omega)$  at high frequencies  $\omega \gg 10^6 \text{ s}^{-1}$ .

### 3.6. Barnett Effect

Because of the Barnett effect (Landau & Lifshitz 1960), a spinning grain will spontaneously develop a magnetization proportional to  $\omega$ :

$$M_{BE} = \chi(0) \frac{\hbar \omega}{g \mu_B} \quad , \quad (16)$$

just as though it were at rest and subject to a magnetic field equal to the “Barnett equivalent” field

$$H_{BE} = \frac{\hbar \omega}{g \mu_B} \approx \frac{0.11}{g} \left( \frac{\omega}{10^6 \text{ s}^{-1}} \right) \text{ Oe} \quad . \quad (17)$$

The fictitious field  $\vec{H}_{BE}$  is antiparallel to  $\vec{\omega}$ . The resulting magnetic moment will cause the grain to precess in the galactic magnetic field (Dolginov & Mytrophanov 1976).

If the grain angular momentum  $\vec{J}$  is not parallel to a principal axis of the moment of inertia tensor,  $\vec{\omega}$  will be time-dependent; Purcell (1979) noted that

there must be resulting dissipation due to the Barnett effect, as the result of which the grain's principal axis of largest moment of inertia must align with the grain angular momentum.

Because  $\vec{H}_{BE} \parallel \vec{\omega}$ , the Barnett effect is not expected to strongly affect the time-dependent magnetization (in the “grain frame”) due to the “oscillating” component of the galactic magnetic field perpendicular to  $\vec{\omega}$ : the effects are expected to be small provided  $H_{BE}$  is small compared to the internal field  $H_i \approx 10^3$  Oe. Thus while the Barnett effect is important for alignment of the grain's principal axis with  $\vec{J}$ , and precession of  $\vec{J}$  around the galactic magnetic field, it is not expected to significantly affect the rate of alignment of  $\vec{J}$  with the galactic magnetic field.

#### 4. Summary

The following are the principal conclusions of this review:

- Irregular grains are subject to radiative torques when illuminated by anisotropic starlight. These torques are likely to result in suprathermal rotation, and to play an active role in the grain alignment process.
- The magnetic properties of grains remain very uncertain. Normal paramagnetism by itself can bring about grain alignment if steady suprathermal rotation can be maintained for long periods.
- The Fe content of interstellar grains is so high that at least part of the grain volume should be ferrimagnetic or ferromagnetic.
- If the ferri- or ferromagnetic inclusions are not too large, they will be superparamagnetic, and can greatly enhance the rate of grain alignment by magnetic dissipation. Fe clusters with diameter  $d \lesssim 90\text{\AA}$  will be effective.
- Even if too large to be superparamagnetic, ferri- or ferromagnetic inclusions in grains may possibly enhance the rate of dissipation in surrounding paramagnetic material.

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